

The background of the slide is a photograph of the Campanile di San Francesco in Honolulu, Hawaii, taken at dusk. The tower is illuminated from within, showing its stone structure and clock faces. The sky is a mix of orange and blue, and the city lights of Honolulu are visible in the distance across the water.

# Large Liquid Scintillator Detectors

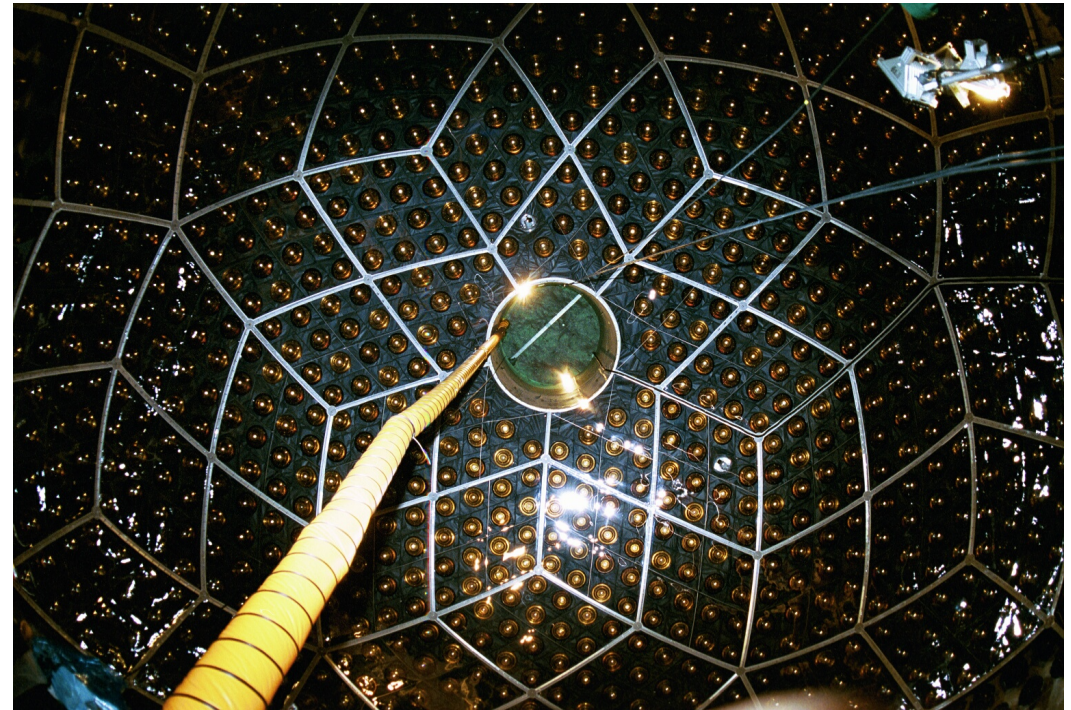
Jelena Maricic,  
University of Hawaii at Manoa  
3<sup>rd</sup> Berkeley Workshop on  
the Direct Detection of Dark Matter  
December 5<sup>th</sup>, 2016

*Many thanks to K. Inoue, H. Watanabe, I. Shimizu, J. Shirai, P. Decowski, N. Rossi, A. Wright, M. Chen...*

# Outline

- Large Liquid Scintillator Detectors (LLSD) overview: performance, usage, advantages and disadvantages
  - Caveat: Focus on monolithic detectors → Will skip segmented detectors (NOVA 14 kton LS)
- KamLAND/KamLAND-Zen instrumentation and scientific journey
- Brief comment on Borexino and SNO+
- Skip JUNO as the focus is more on the experience of the current generation

## Summary

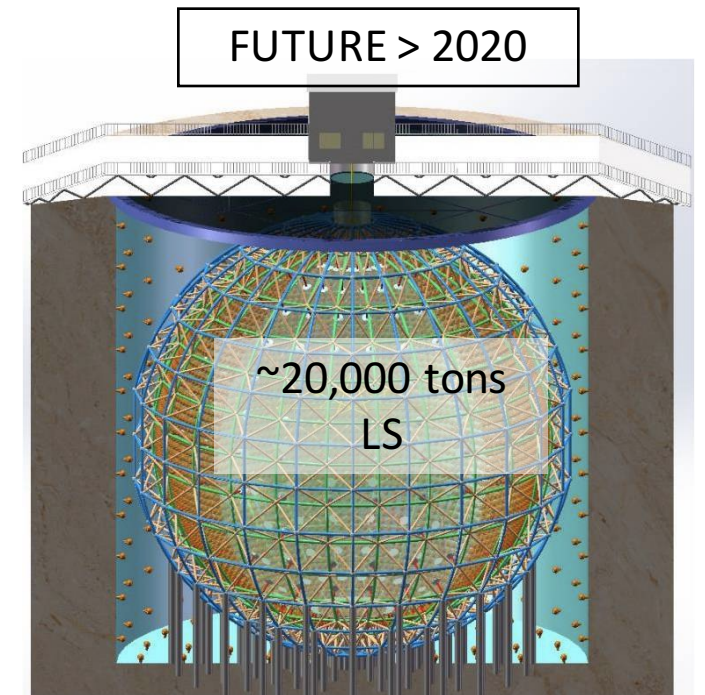
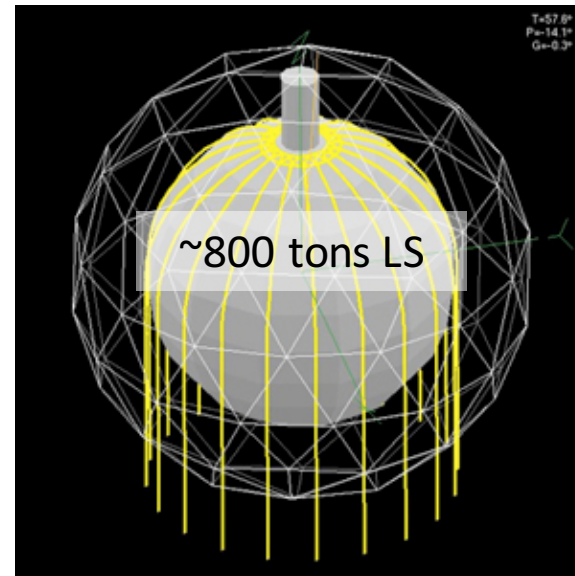
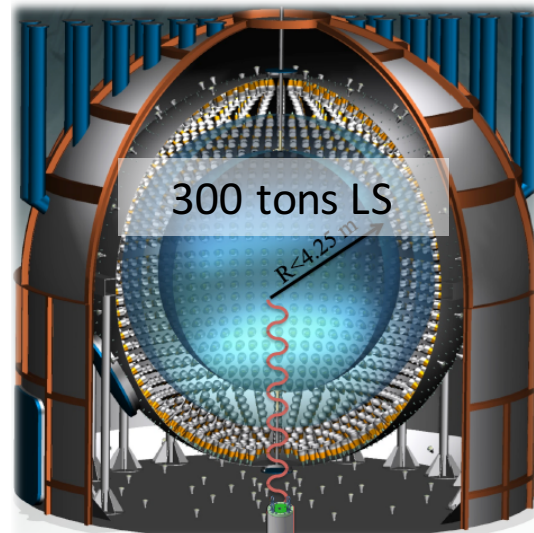
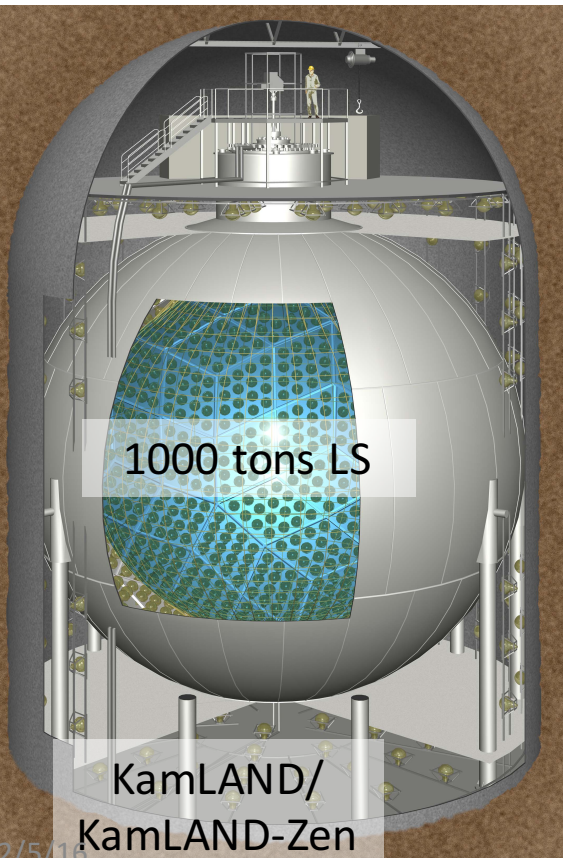


*The view of the KamLAND top from inside.*



# Large Liquid Scintillator Detectors (LLSD)

- A very privileged club: detector volume measured in 100s of tons of liquid scintillator (LS)
- Multiple applications: neutrinoless double beta decay (NDBD), neutrino oscillations, neutrino mass ordering, solar physics, sterile neutrino search, geoneutrinos for geology
- Use: reactor vs, solar vs, geo vs, source vs, supernovae vs



FUTURE > 2020

Borexino/SOX

SNO+

JUNO

J. Maricic, Large Liquid Scintillator Detectors

# Performance of LLSDs

- Calorimetric detectors - full energy containment allows:
  - Full spectral fit
  - Vertex reconstruction
  - No escape or invisible energy of  $\beta$ ,  $\gamma$   $\rightarrow$  background identification relatively easy
- Significant self-shielding from external gamma-rays and neutrons
  - LS is hydrogen rich – excellent at stopping and capturing both fast and radiogenic neutrons  $\rightarrow$  attractive veto for DM hunting
- LS is intrinsically radio pure  $\rightarrow$  further purification by distillation (demonstrated to work)
- Minimal detector material  $\rightarrow$  example:  $\sim 25\mu\text{m}$  thick nylon film holding LS
- Straightforward scalability of target volume in case of NDBD
- **BUT**: relatively poor energy resolution (few percent)  $\rightarrow$  can be improved
  - Addressed by higher PPO concentration in LS, greater photodetector coverage, higher quantum efficiency for PMTs and light concentrators.







# KamLAND-Zen Collaboration



March, 2016

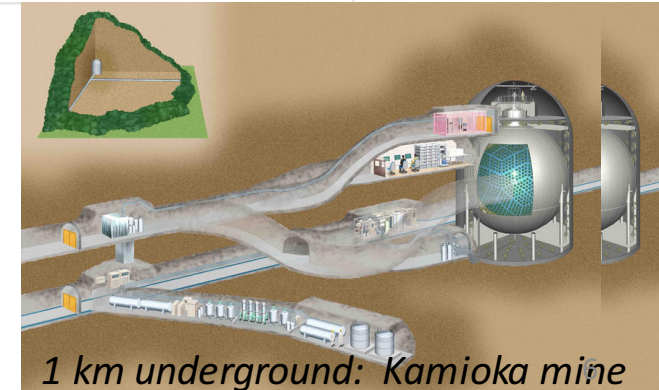
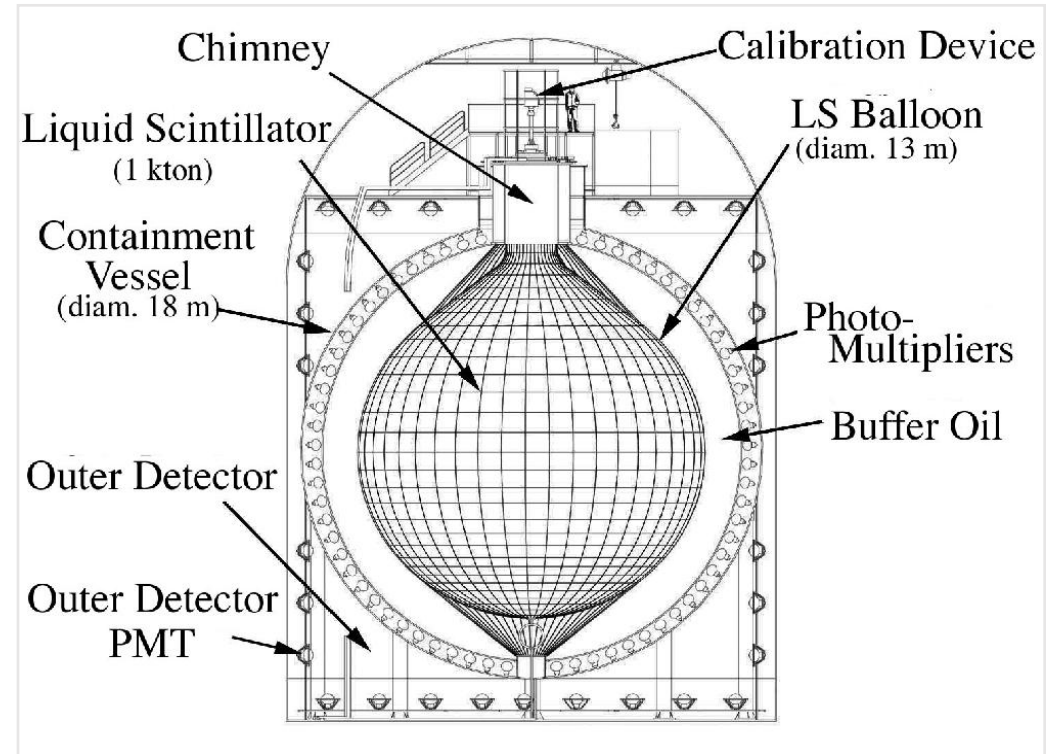
## KamLAND/KamLAND-Zen Instrumentation and Scientific Journey

# KamLAND Detector Scheme

- 1kton of LS surrounded by buffer oil and acrylic Rn barrier.
- 1325 17" PMTs
- 554 20" PMTs
- 34% photocatode coverage
- 225 20" PMTs - veto water Cherenkov detector
- 300 p.e./MeV observed at the center.

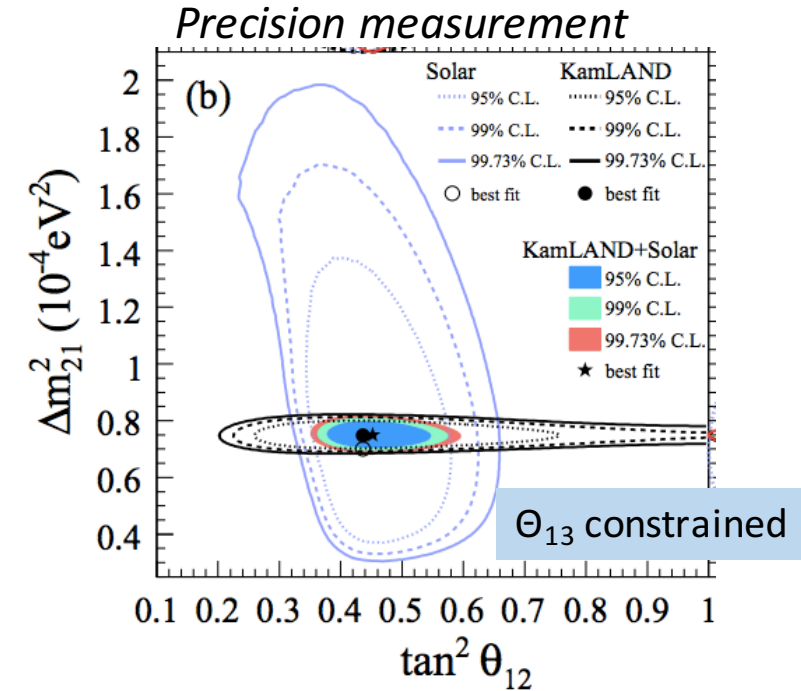
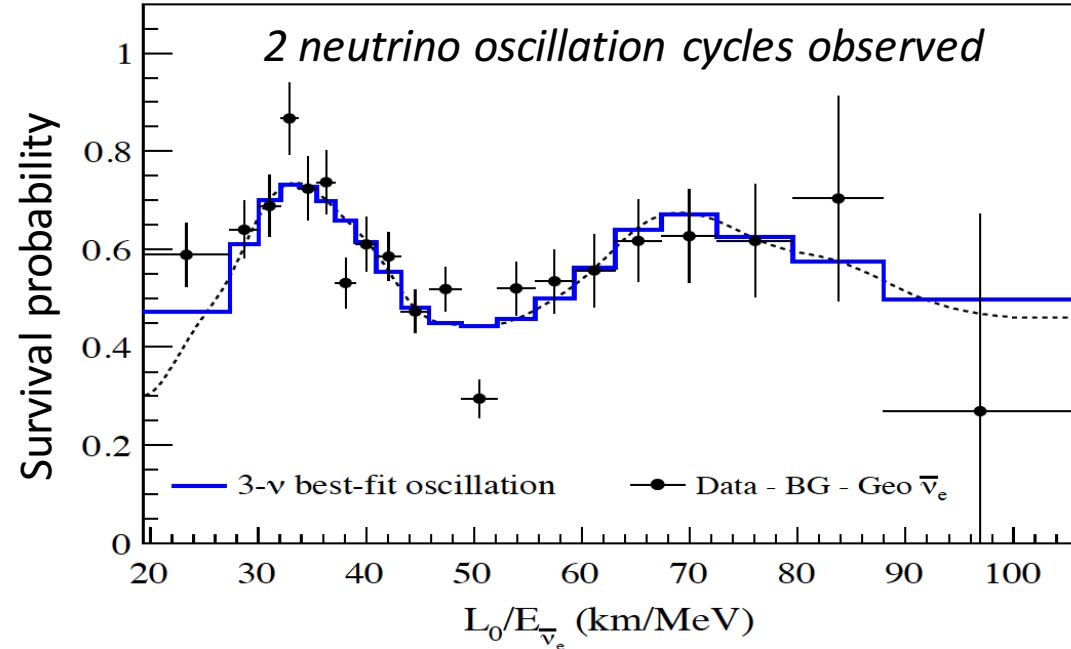
\*Outstanding LS radiopurity:

U	$(3.5 \pm 0.5) \times 10^{-18}$ g/g
Th	$(5.2 \pm 0.8) \times 10^{-17}$ g/g
K	$< 2.7 \times 10^{-16}$ g/g

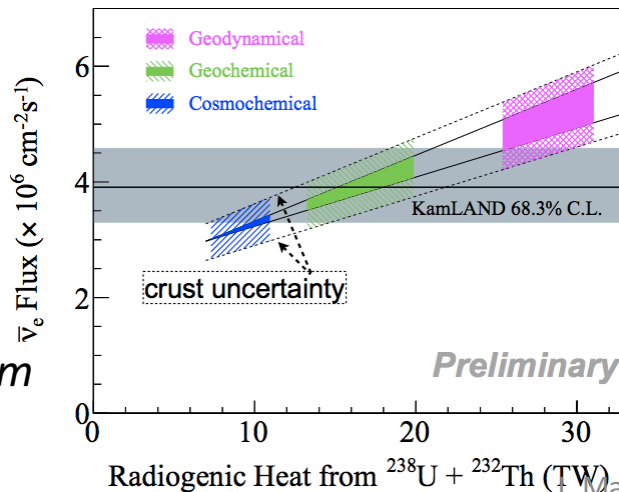




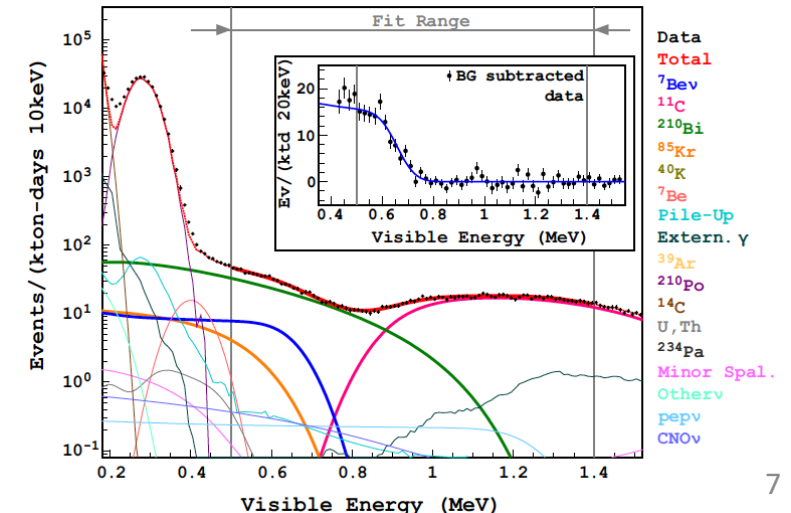
# KamLAND Neutrino Oscillation and Geoneutrino Results



Geoneutrino spectrum  
And radiogenic heat  
measurement

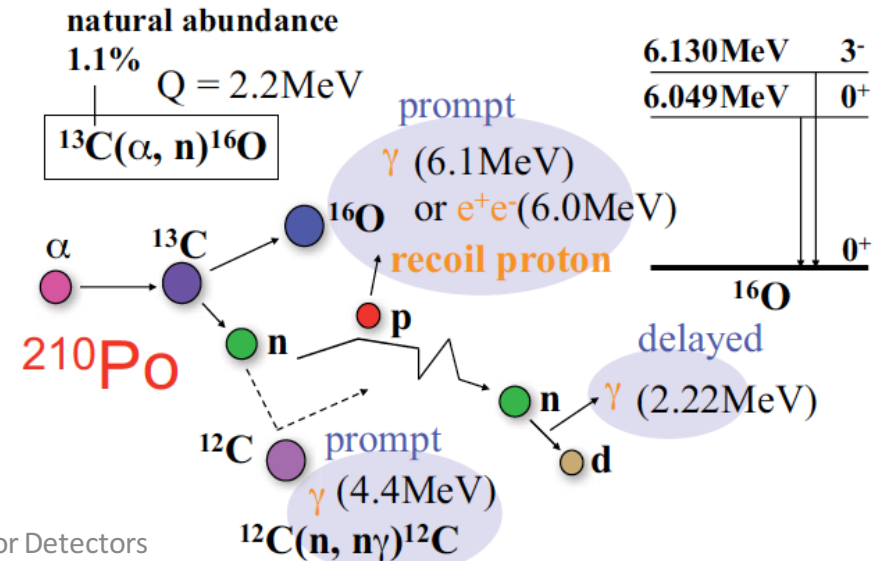
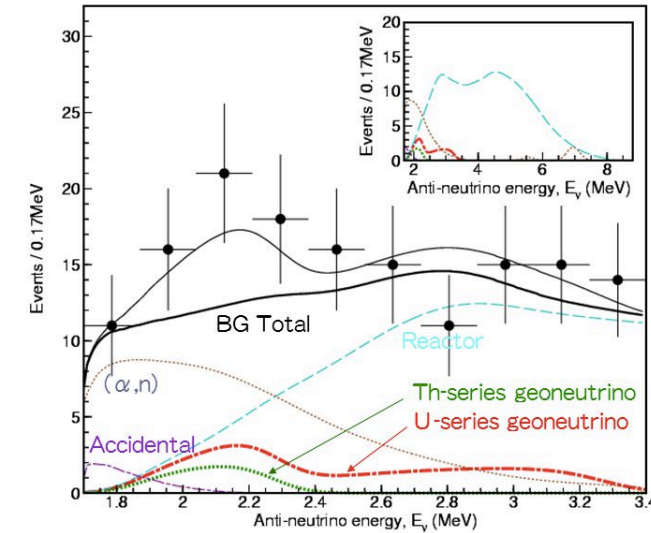
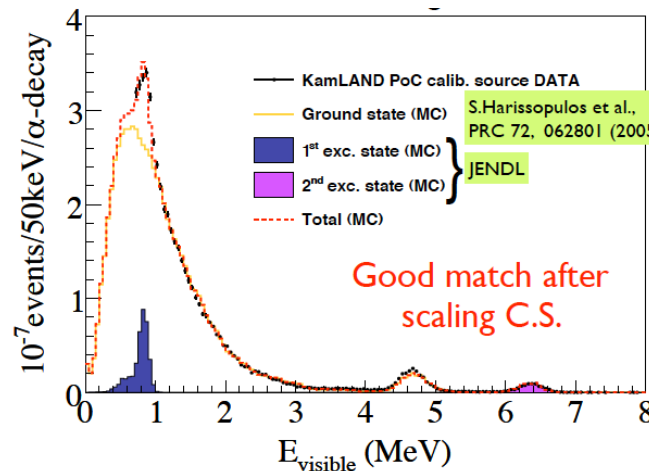
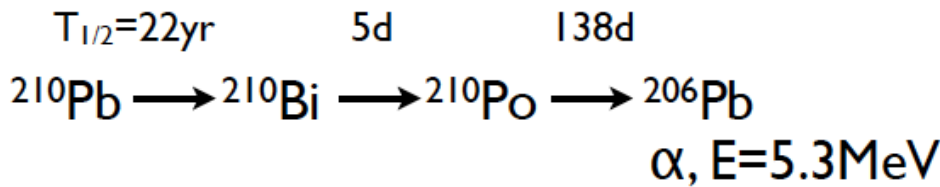
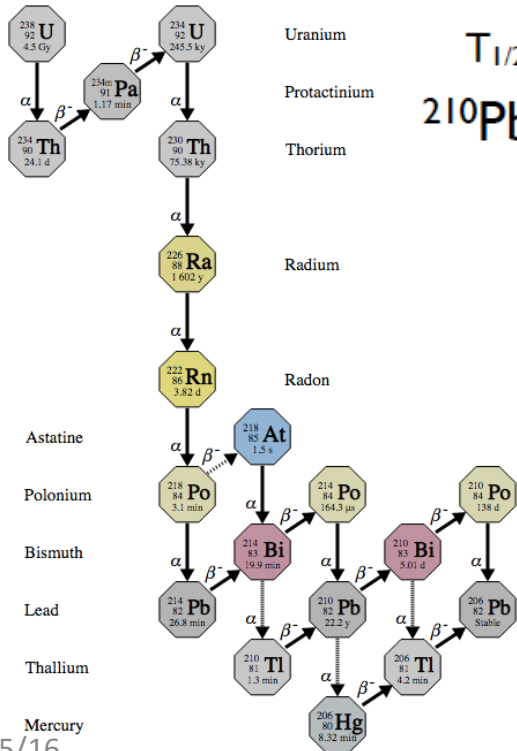


$^7\text{Be}$  solar  $\nu$  measured  
With well understood  
backgrounds



# Toward $^7\text{Be}$ solar neutrino measurement

- When the first internal analysis of geoneutrinos was launched, a large signal was observed  $\rightarrow$  way above Earth model predictions
  - New background was identified
  - LS was contaminated with  $^{210}\text{Pb}$ , daughter of  $^{222}\text{Rn}$ , part of the  $^{238}\text{U}$  chain
  - Concentration of  $^{222}\text{Rn}$  in mine air 10 times higher than outside
  - This was also a serious background for  $^7\text{Be}$  solar neutrino measurement

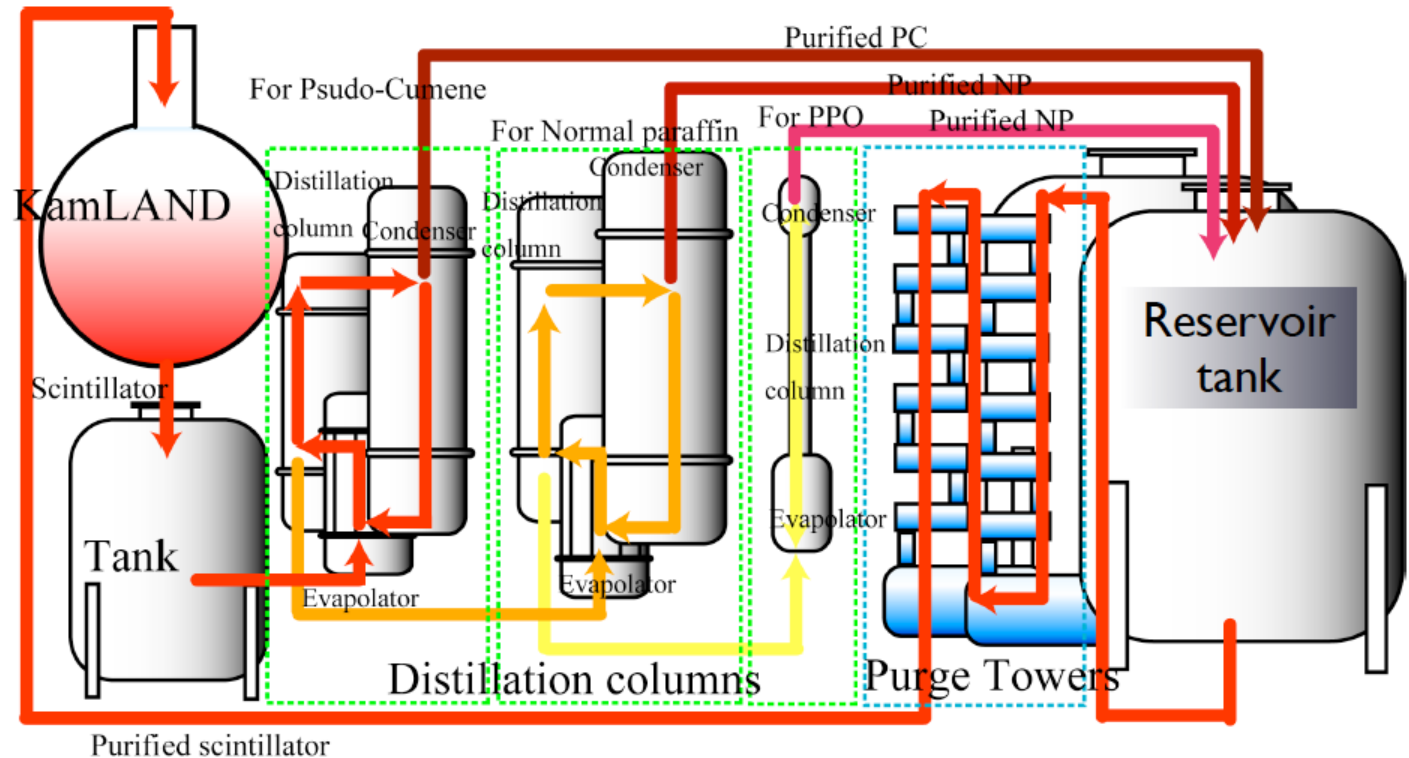




# Purification campaigns to reduce $^{210}\text{Pb}$ and other contaminants 2007 - 2008



- 2 distillation campaigns to remove  $^{210}\text{Pb}$
- Included  $\text{N}_2$  purge to remove  $^{85}\text{Kr}$  and  $^{39}\text{Ar}$



LS is distilled into MO, PC and PPO, remixed and purged with  $\text{N}_2$ .

# Purification campaign results

- The first campaign (2007) less successful due to some mixing of unpurified and purified LS
- In the second campaign: strict control of LS density and temperature
- Total circulation: 5.6 times full volume = 1669 m<sup>3</sup> (campaign I) + 4856 m<sup>3</sup> (campaign II)

## Reduction rates:

$^{85}\text{Kr} \rightarrow 6 \times 10^{-6}$

$^{210}\text{Bi} \rightarrow 8 \times 10^{-4}$

$^{210}\text{Po} \rightarrow 5 \times 10^{-2}$

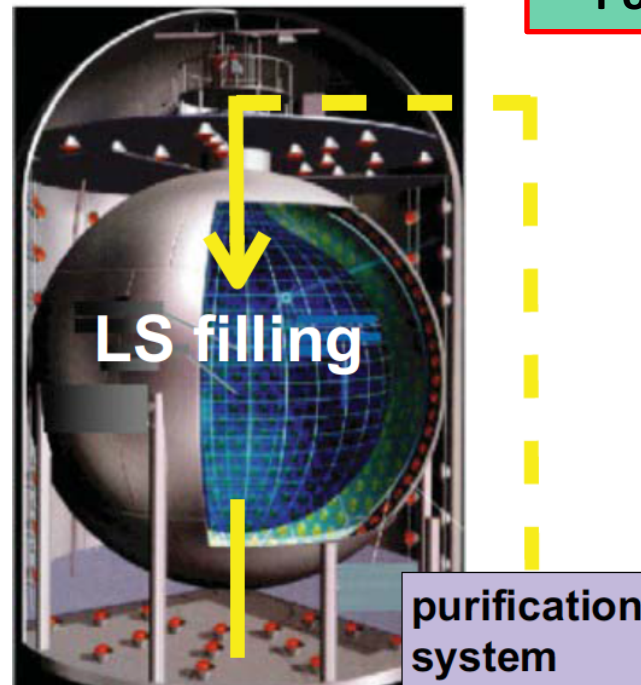
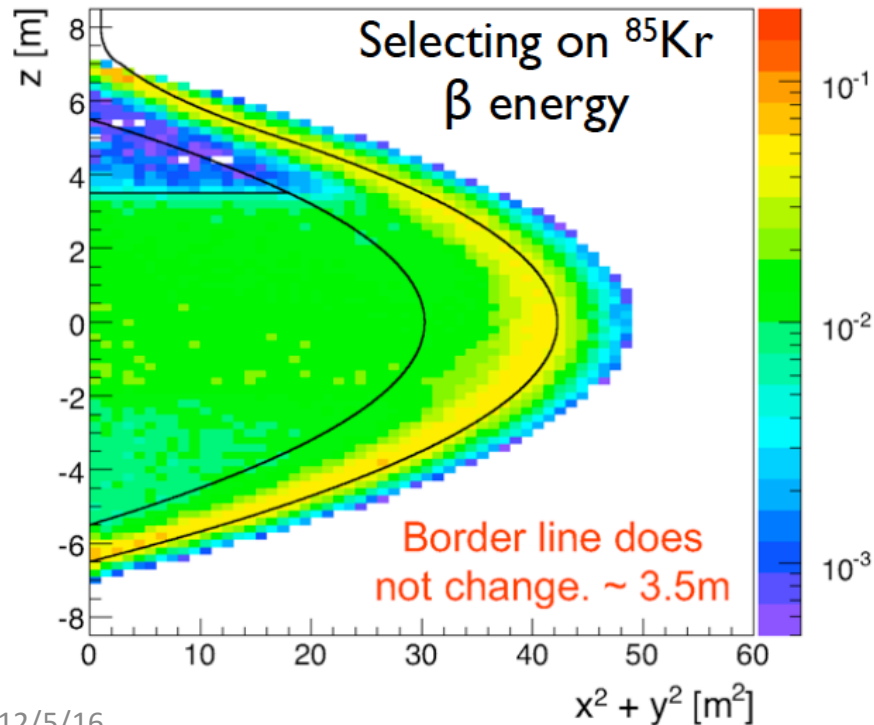
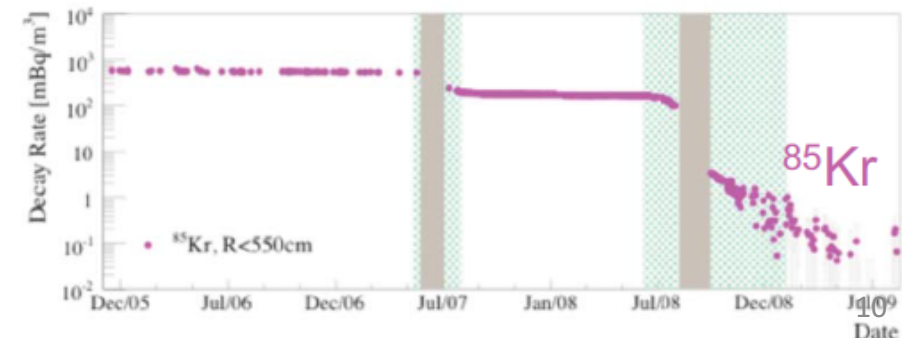
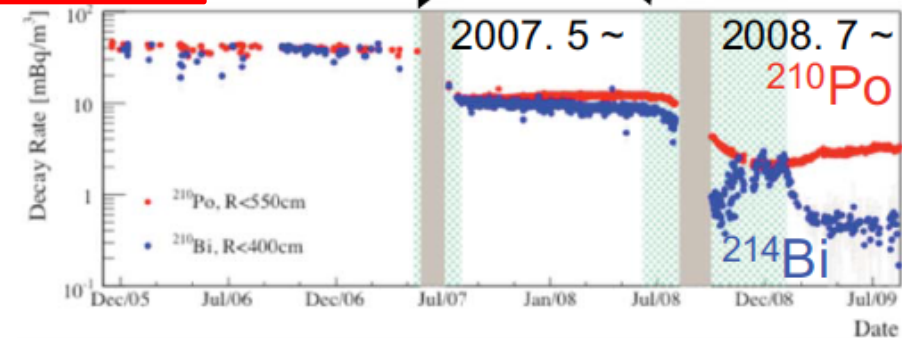
## LS purification

1st

2nd

2007. 5 ~

2008. 7 ~



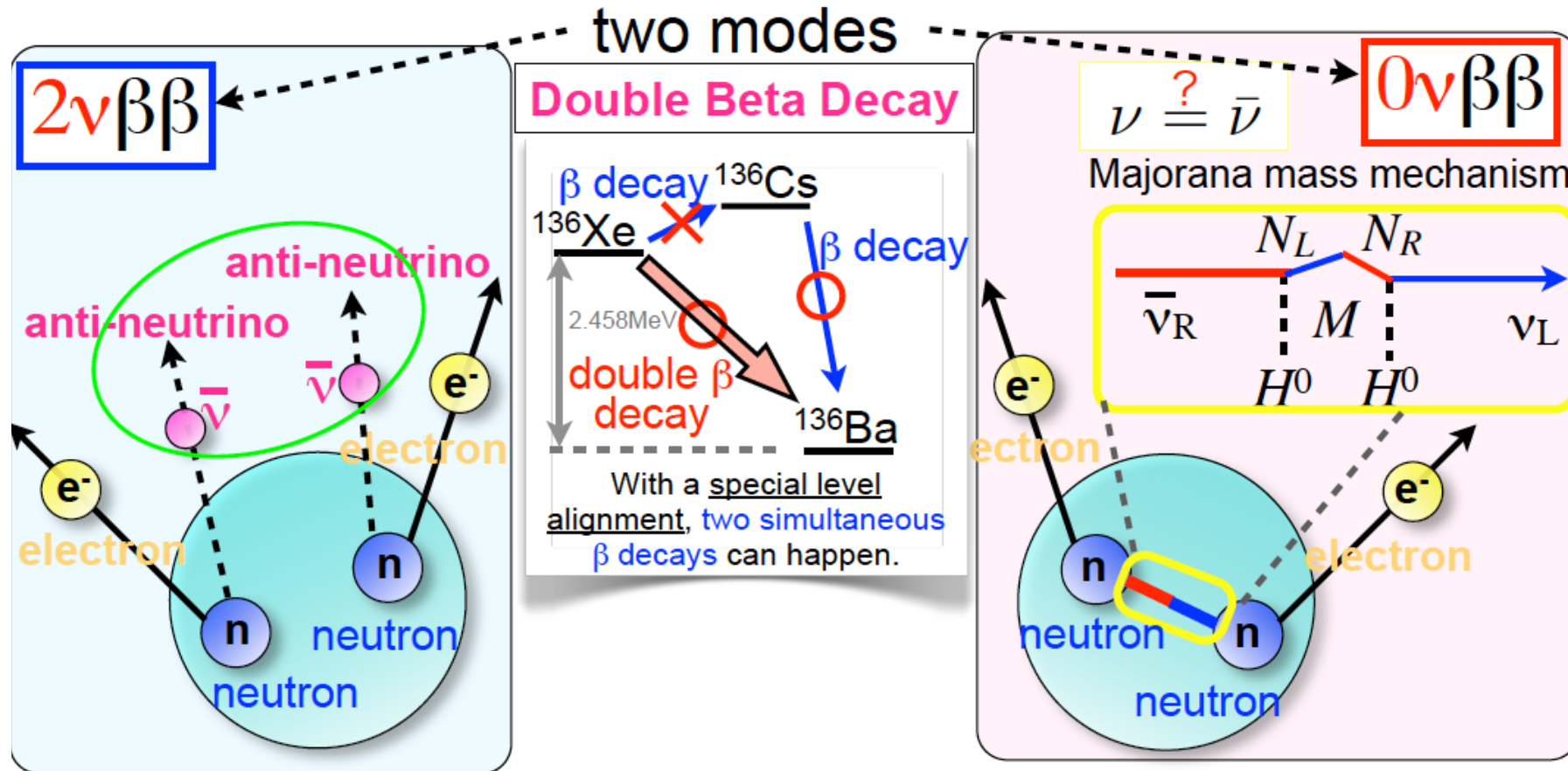
J. Maricic, Large Liquid Scintillator Detectors



# KamLAND-Zen – NDBD Experiment

## *Retrofitting detector for rare event search*

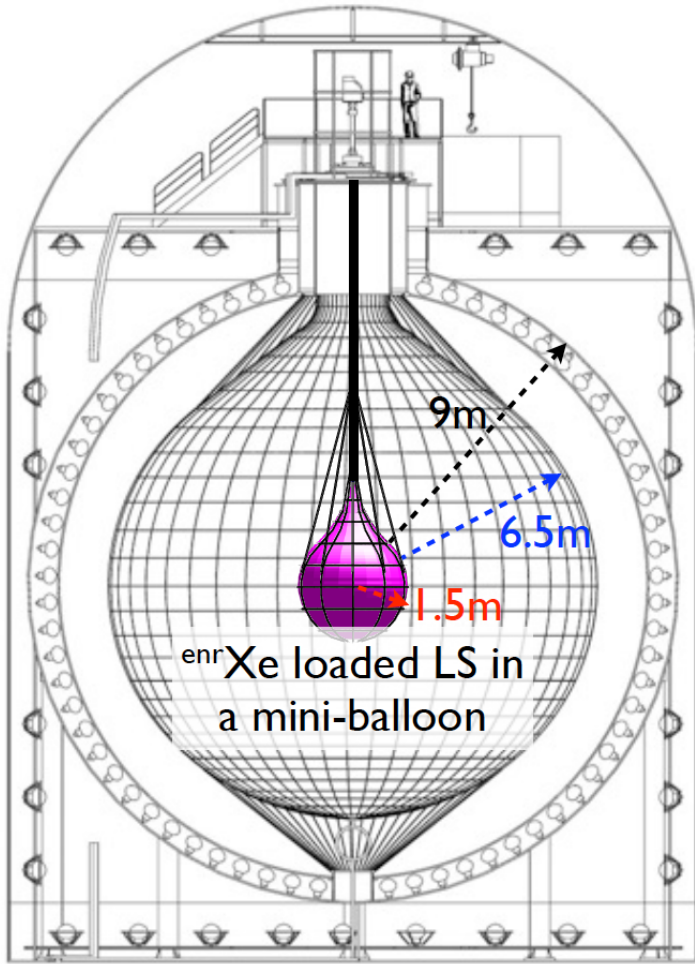
### Neutrinoless Double Beta Decay



- Second order process.
- Half life has been observed for several nuclei.

- Forbidden in the Standard Model (lepton number violation)
- Its observation would constitute proof that neutrinos are Majorana leptons.

# KamLAND-Zen: NDBD with $^{136}\text{Xe}$



- Operational detector
  - relatively low cost:  $^{136}\text{Xe}$  + mini-balloon (MB)
  - & quick start: '09 (funding received) – '11 (KZ start)
- LLSD + clean → negligible external gammas
  - Only needs very clean Xe and MB*
- Xe-LS easily purified and MB replaceable as needed
  - straightforward scalability to several tons of Xe
- Background cross-check by running in different conditions – with enriched Xe, no Xe (dummy LS)
- No escape or invisible energy from  $\beta$ ,  $\gamma$ 
  - BG identification fairly simple
- *Continued detection of geoneutrinos with Japanese reactors off.*



# Balloon Production and Installation

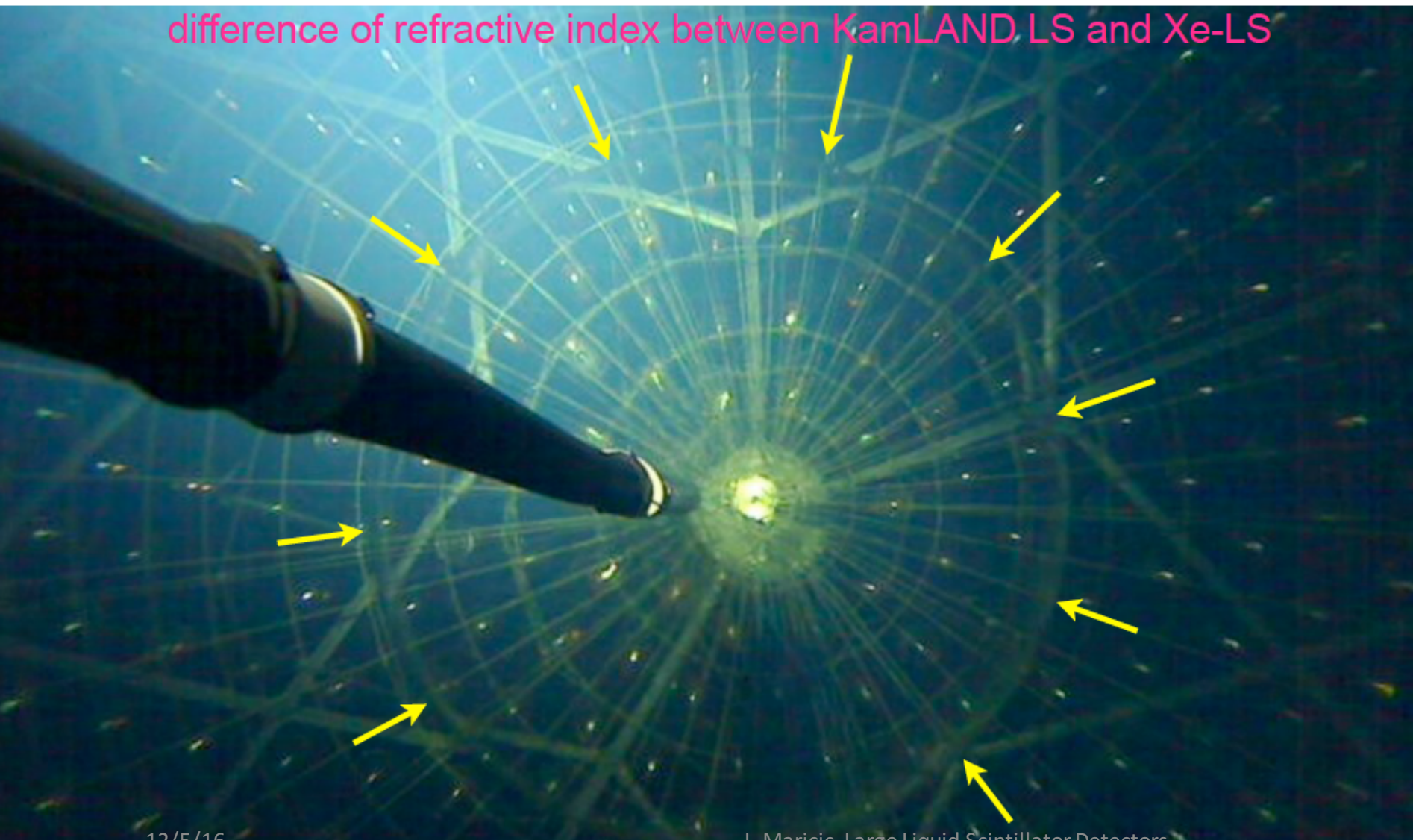


- MB: mechanical strength, Xe barrier (<1kg/yr)
- Nylon film OK (EVOH not strong enough)
- Minimizing backgrounds:
  - MB made with thin and clean film
- Balloon first filled with dummy LS
- Then dummy LS replaced with Xe LS



# Balloon Installed

difference of refractive index between KamLAND LS and Xe-LS



Minimum inactive detector material:  
25  $\mu\text{m}$  thin balloon film.  
Backgrounds on balloon surface are of great concern.

Balloon produced in very clean conditions.

Brand new LS used to load with Xe.

Xe distillation as well.



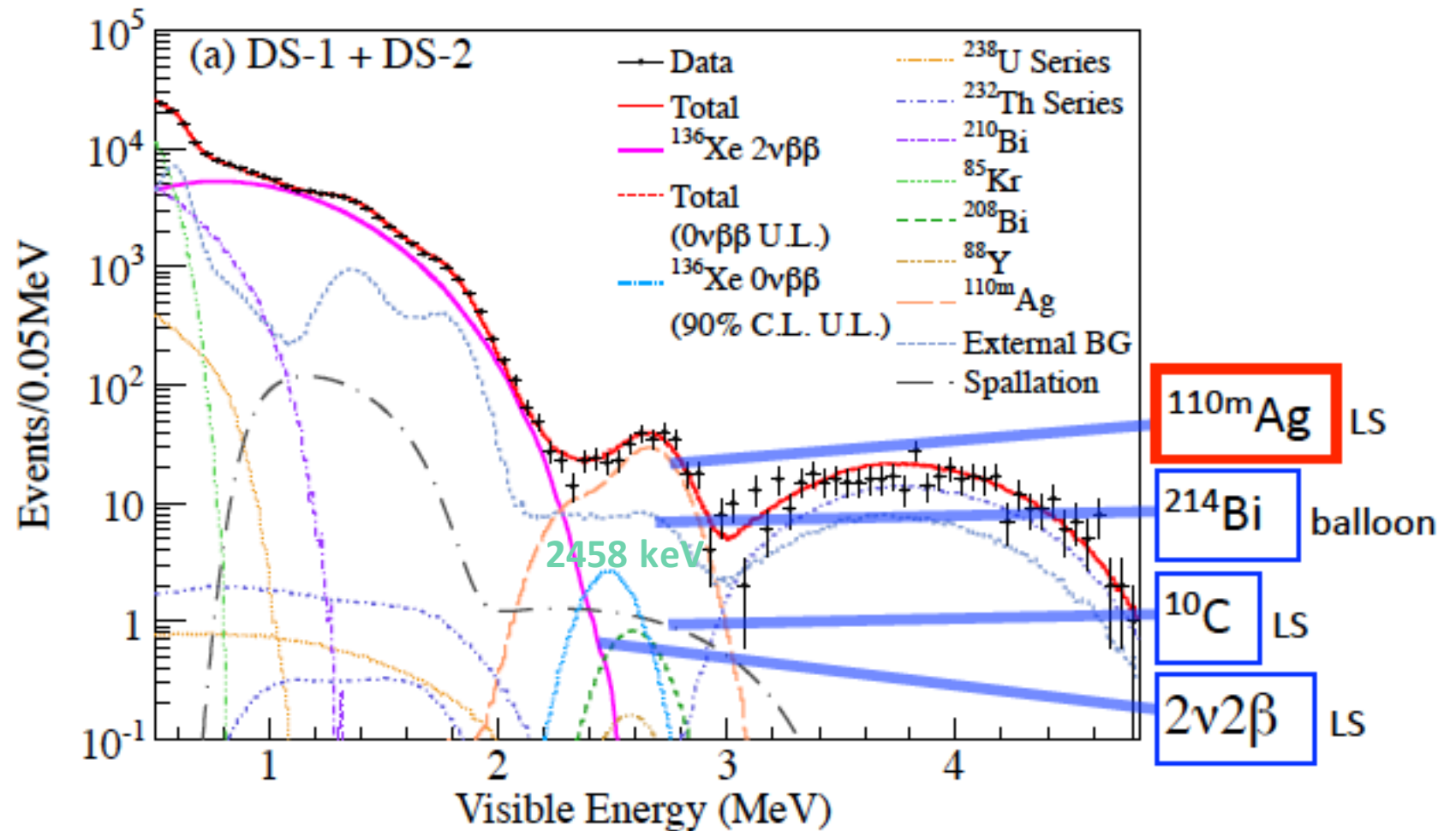
# KamLAND-Zen Phase I – 89.5 kg yr

- Balloon deployed and filled Xe loaded LS in 2011

Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

$$\sigma_E(2.5\text{MeV}) = 4\%$$

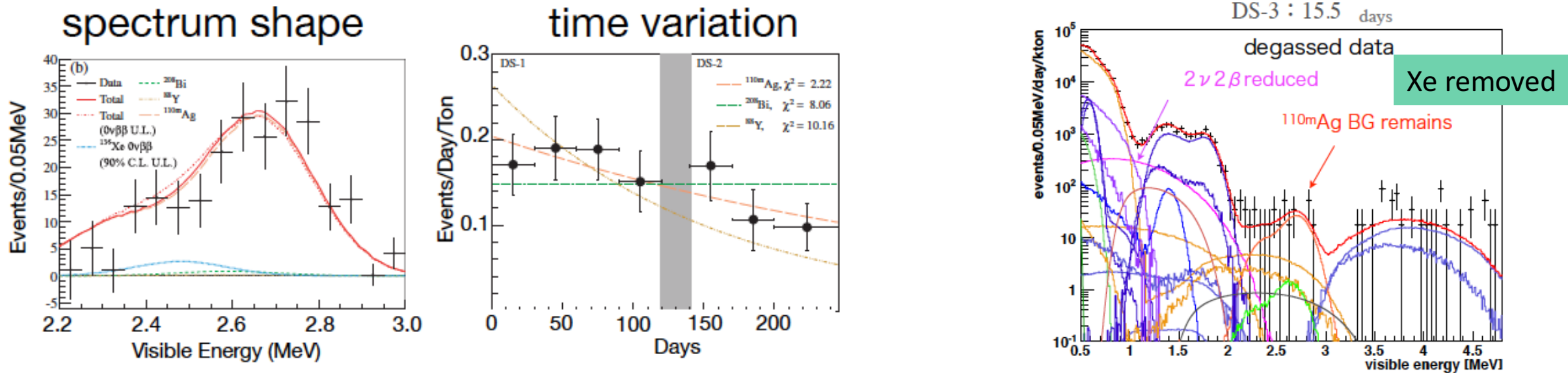
- An unexpected background found dominating  $0\nu\beta\beta$  region



$$T^{0\nu}_{1/2} > 1.9 \times 10^{25} \text{ yr (90\% C.L.)}$$

# Source of Unexpected Background

- Background traced back to Fukushima accident – fallout from the accident introduced  $^{110m}\text{Ag}$  in March 2011, at the time of MB construction.
- No escape  $\beta$ ,  $\gamma$  – background spectrum shape fitting made easy

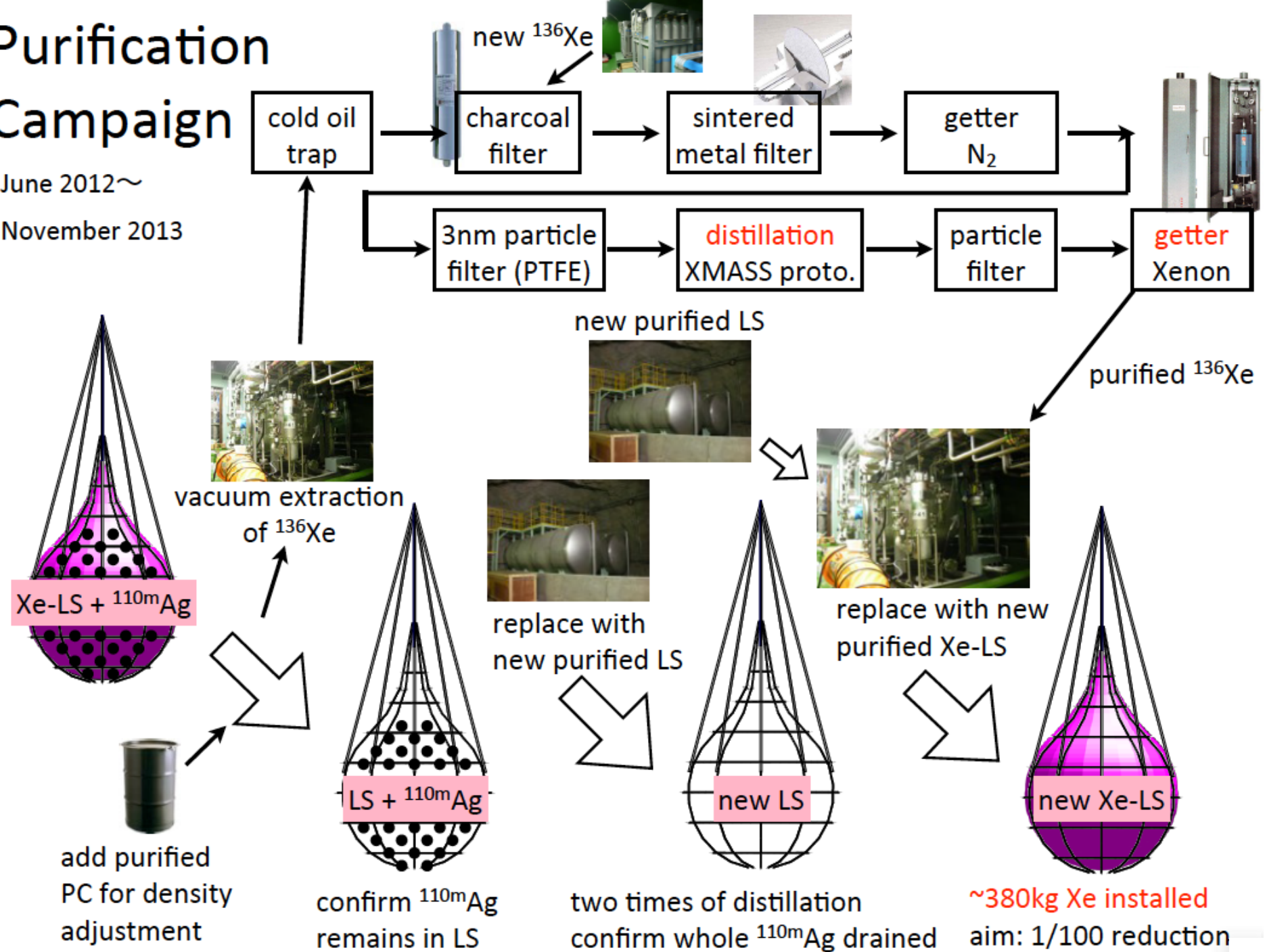


- Consistent with  $^{110m}\text{Ag}$  ( $Q = 3.01$  MeV,  $T_{1/2} = 260$  days)
- Purification of Xe loaded LS necessary

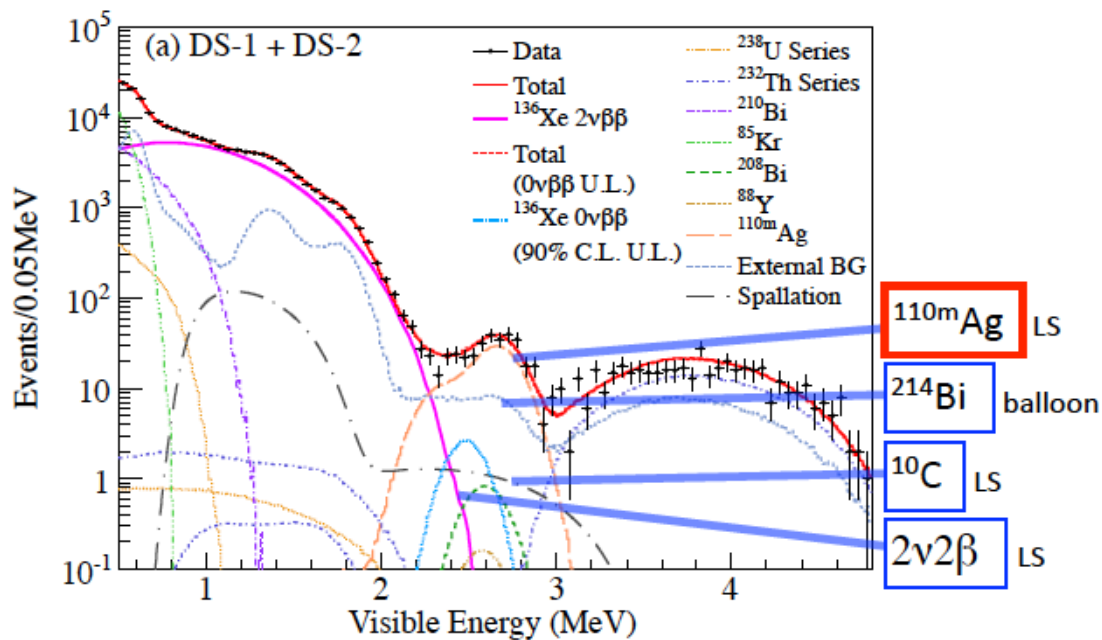
# Purification Campaign

June 2012~

November 2013

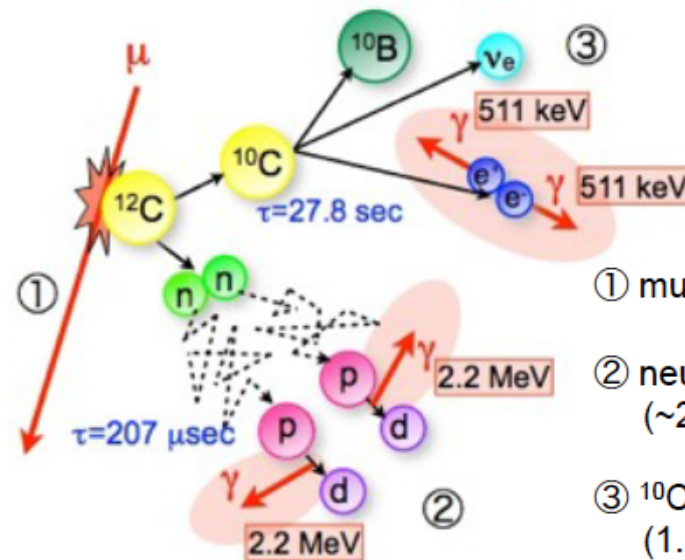






# What about other backgrounds?

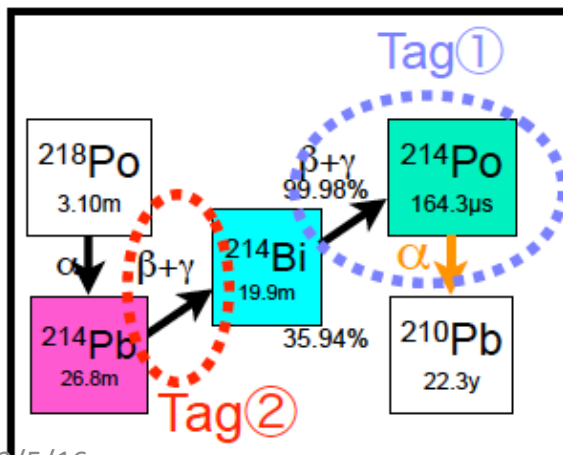
## ► $^{10}\text{C}$ from muon spallation



- Throughout volume
- 3 fold-coincidence
- Dead-time free electronics



## s ► $^{214}\text{Bi}$ background tagging



### Tag① $^{214}\text{Bi}/^{214}\text{Po}$ delayed coincidence

Transparent efficiency of  $\alpha$  particle from  $^{214}\text{Po}$  decay is important for Tag①.

Thin film is better.

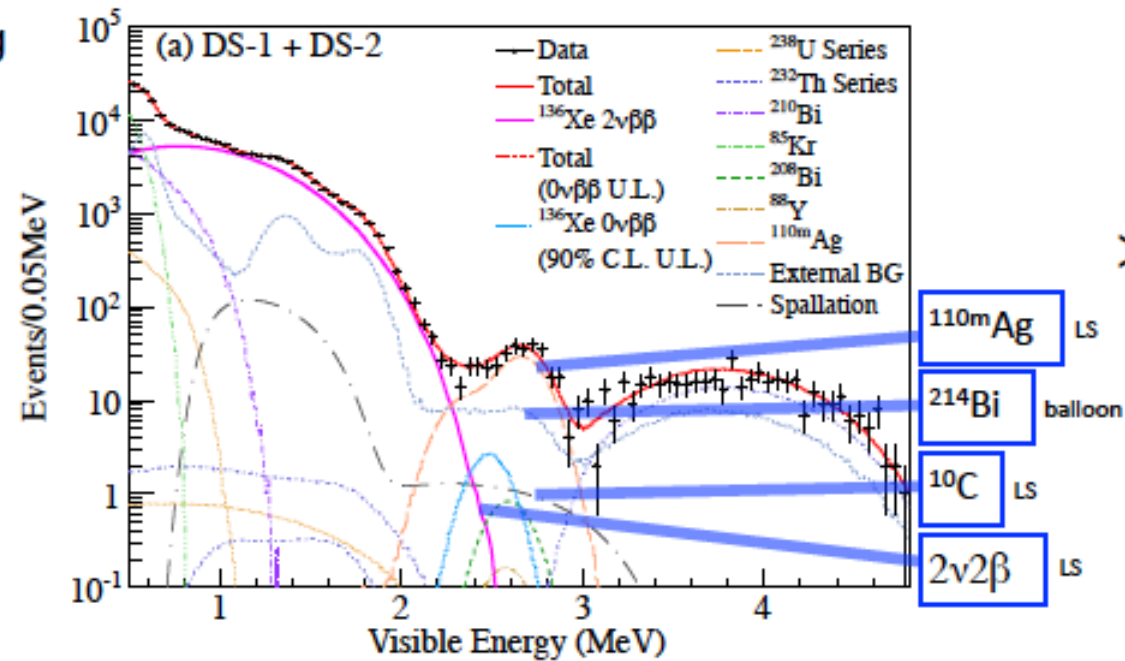
### Tag② $^{214}\text{Pb}/^{214}\text{Bi}$ event

Tag② uses vertex correlation between  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  event

Control accidental coincidence is important. Reduce  $^{40}\text{K}$  contamination in film.

- MB surface background
- Fine volume binning

Phase-1 320kg  
before  
purification

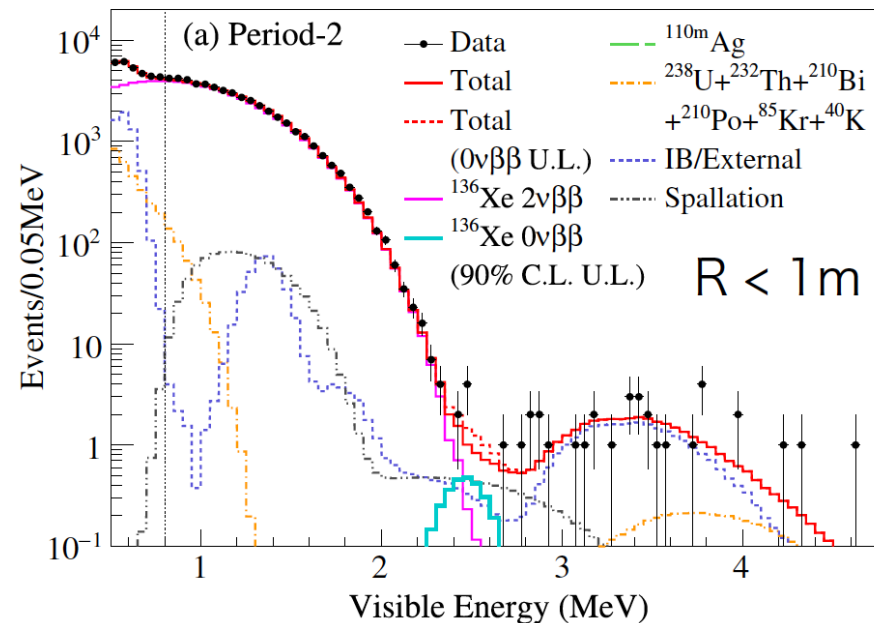


$>1.9 \times 10^{25} \text{y}$

Phase-2 380 kg

After purification

$^{110\text{m}}\text{Ag}$  reduction  $< 1/10$

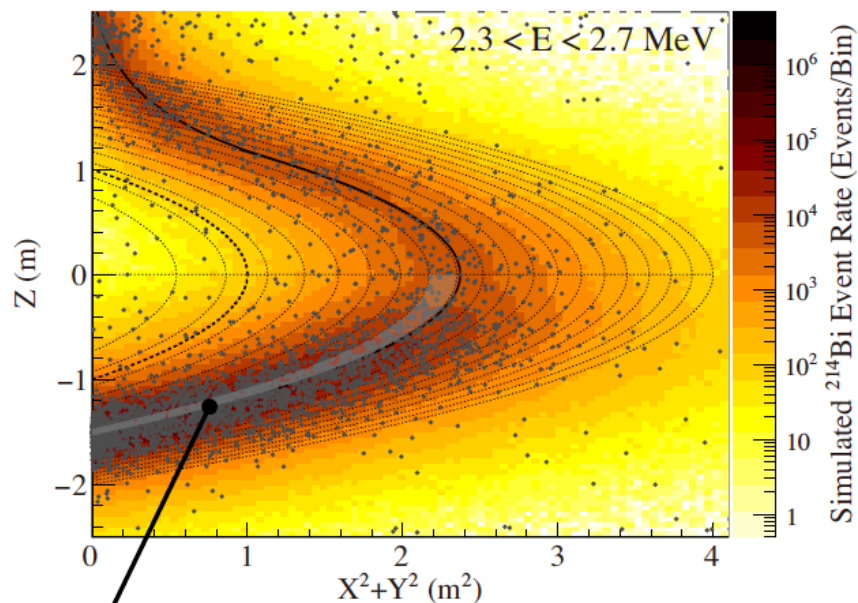


2013/12/11 – 2014/10/27  
534.5 days (504 kg-yr)

**IN-SITU  
PURIFICATION  
POSSIBLE!**

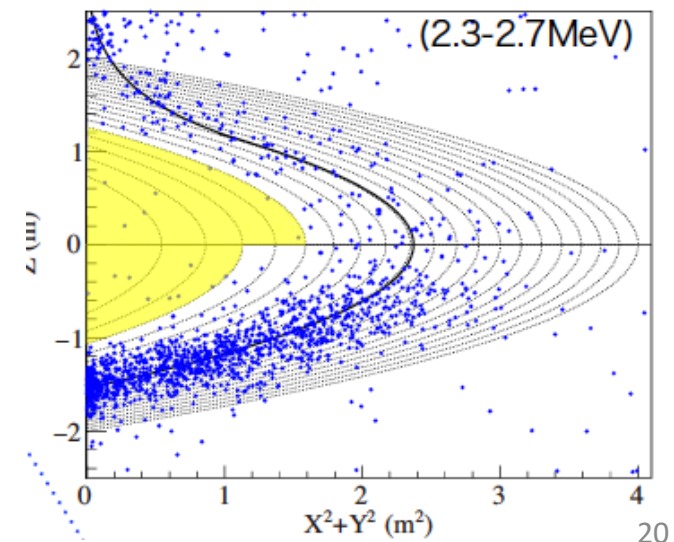
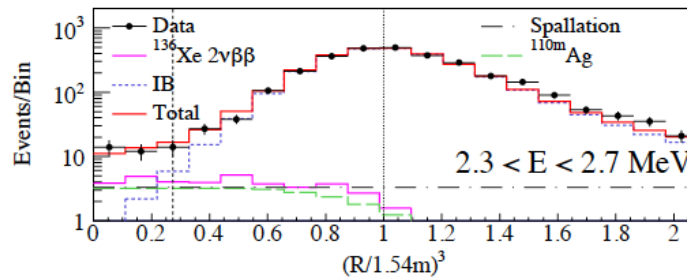
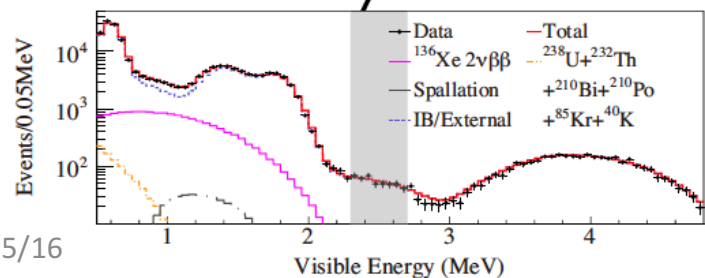
# Further Improvement of Sensitivity

- To reduce backgrounds from MB film contamination – all volume, time-binned analysis
- 40 equal volume bins! Radial cut:  $R < 1$  m
- Source calibration at the end of the run to determine energy and vertex resolution



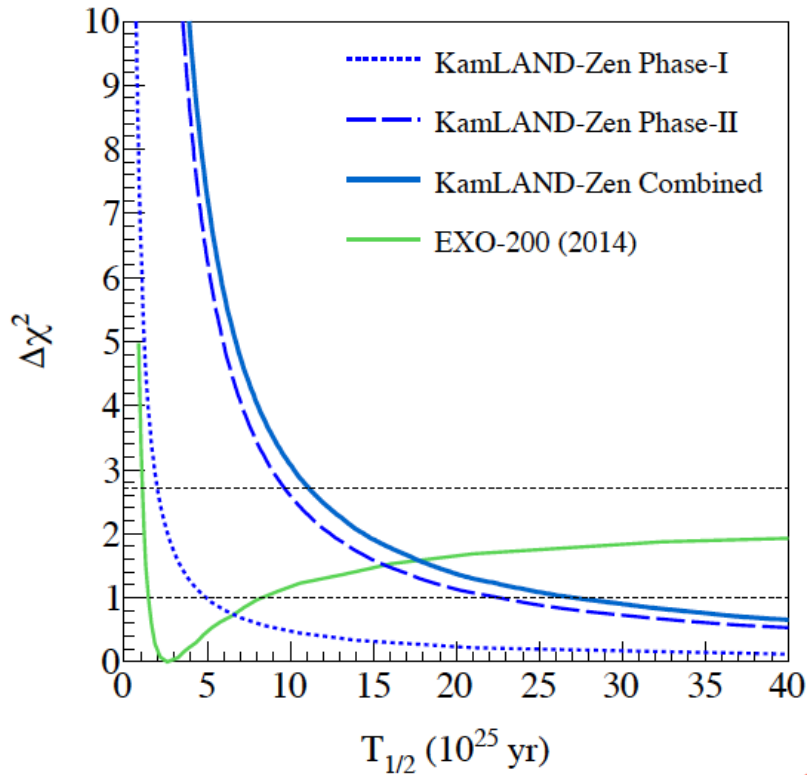
Energy and radial distribution well reproduced by known backgrounds.

use FV for period-2 data  
upper hemisphere  $R < 1.26$  m (5 bins)  
lower hemisphere  $R < 1.06$  m (3 bins)



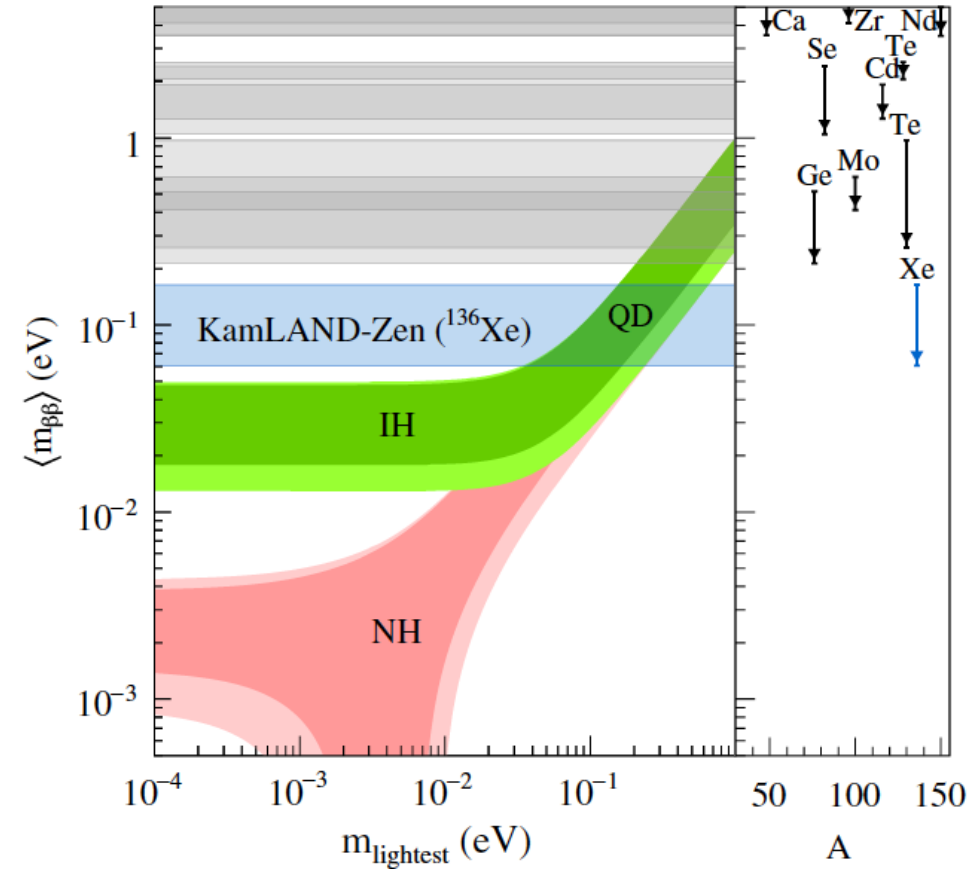


# Final Combined KamLAND-Zen 1&2 phase result



$$T_{1/2}^{0\nu} > 1.07 \times 10^{26} \text{ yr}$$

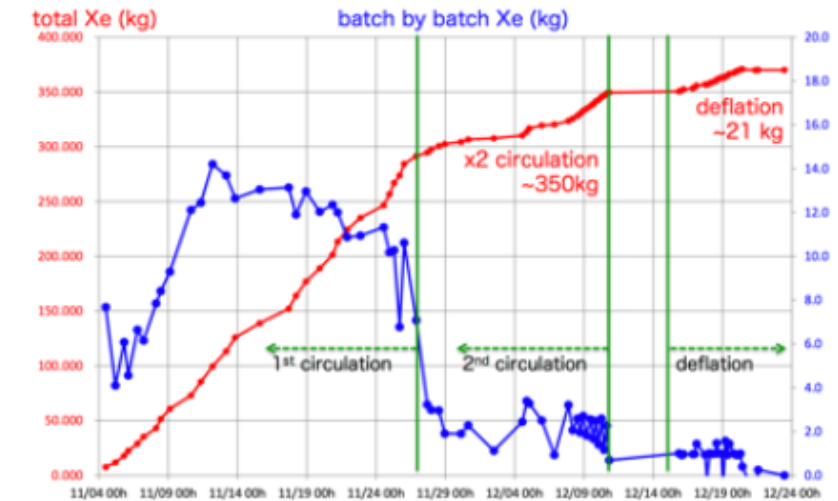
$$\langle m_{\beta\beta} \rangle < (61 - 165) \text{ meV}$$



- The best limit overall!
- Getting closer to Inverted Hierarchy region!

# Next phase: KamLAND-Zen 800

- The MB has been removed in December 2015 →  
→ all Xe recovered during recirculation and MB deflation  
(for tank inspection required by law)
- Search with 750 kg of enriched Xe → improve sensitivity to better than 50 mV.
- Reduce film background due to dust → fabricated new, cleaner and larger balloon
- Further optimize  $^{10}\text{C}$  triple-fold coincidence
- Nothing can be done about 2v background without further improving energy resolution  
(planned for KamLAND-II)



# Example of improvements

before



after



clean  
underwear



changing  
room in a  
clean room

keep staying away  
goggle  
welding machine  
cover sheet .  
glove on glove  
laundry twice a day .  
clean underwear .



laundry  
twice a day

changing room in a clean room .  
dust visualization  
more neutralizer



cover  
sheets

2<sup>nd</sup> MB fabrication  
Cleaning a lot  
With improvements...

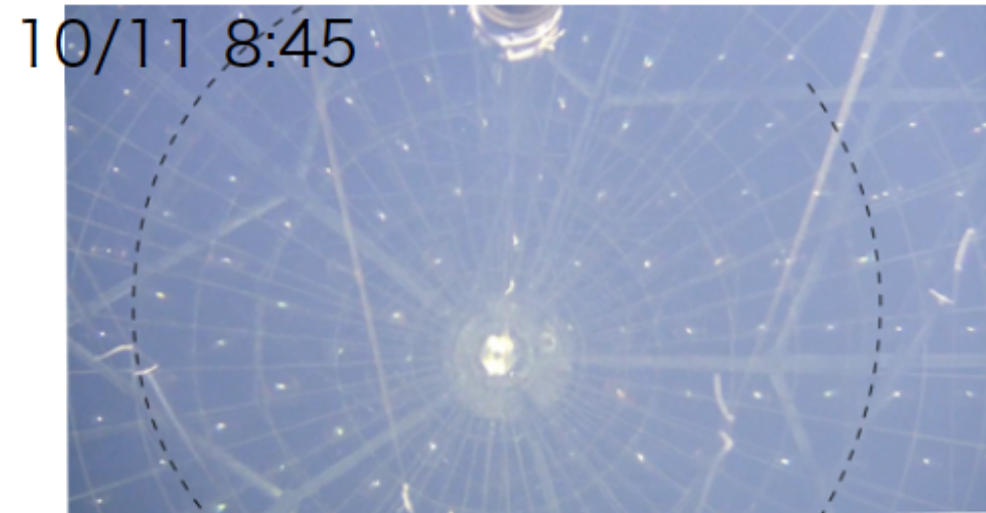
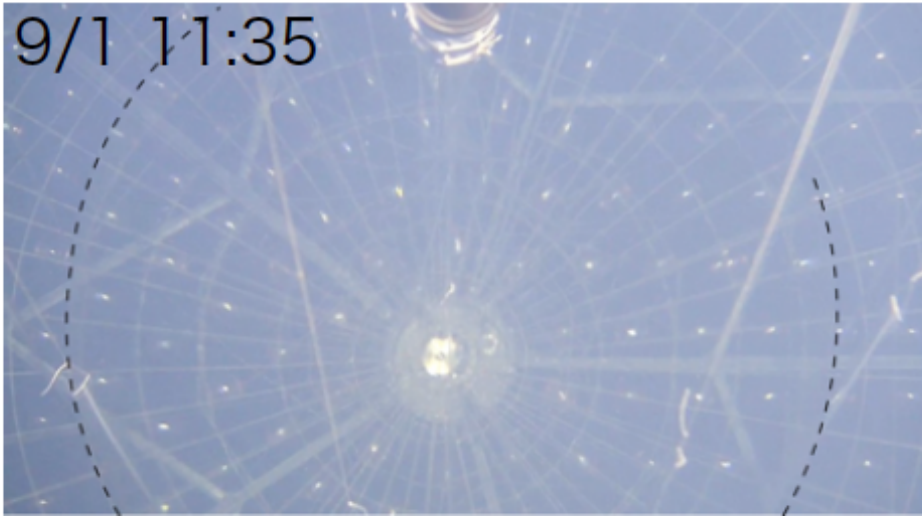


We confirmed that the mini-balloon is cleaner !!

Measures we took worked!

2<sup>nd</sup> MB deployed in  
August 2016

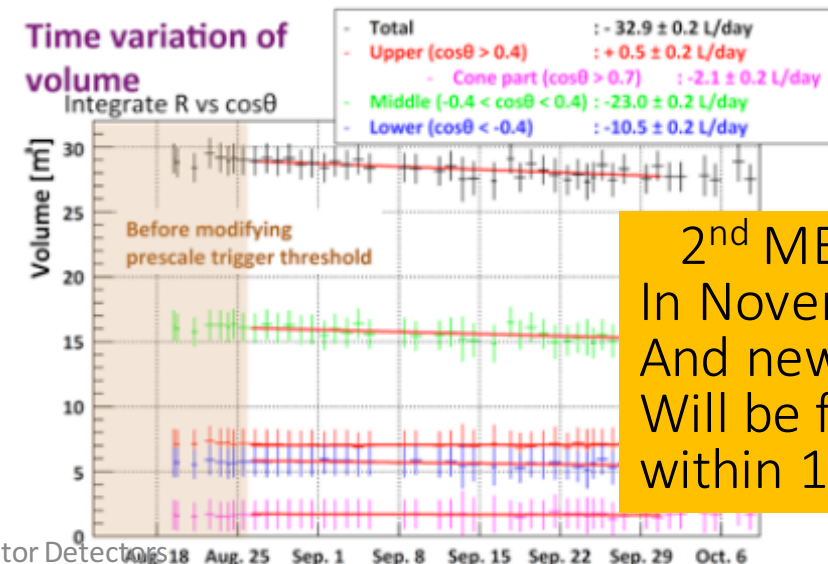
At the same time, we noticed;



Indications of leak;

- camera image
- load cell
- balloon shape reconstruction with  $^{210}\text{Po}$  events
- $^{222}\text{Rn}$  decay rate
- mixture of KL-LS and dummy-LS

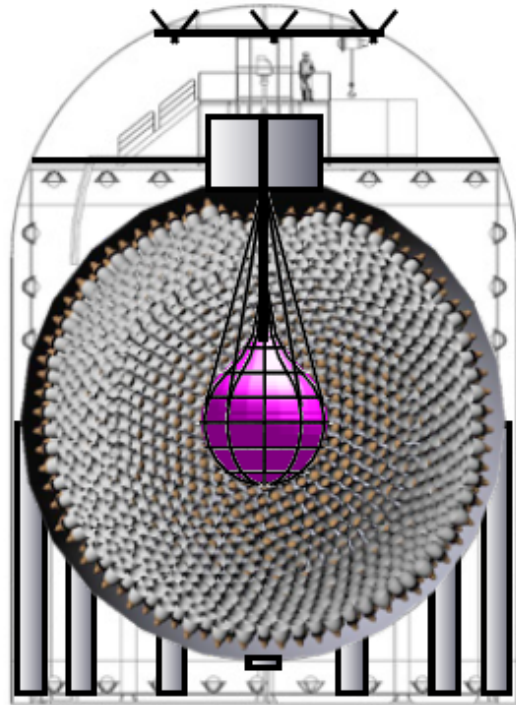
by gas-chromatography



2<sup>nd</sup> MB removed  
In November 2016  
And new balloon  
Will be fabricated  
within 1 year

# Higher energy resolution for reducing $2\nu$ BG

⇒ KamLAND2-Zen



1000+ kg xenon



Winston cone

light collection  $\times 1.8$

high q.e. PMT

light collection  $\times 1.9$

17"  $\phi \rightarrow 20"$   $\phi$   $\epsilon = 22 \rightarrow 30\%$

New LAB LS

light collection  $\times 1.4$

(better transparency)

expected  $\sigma(2.6\text{MeV}) = 4\% \rightarrow \sim 2\%$

target sensitivity 20 meV

## And more?

Pressurized Xe  
Scintillating film  
Imaging for  $\beta/\gamma$  id.



## Super-KamLAND-Zen

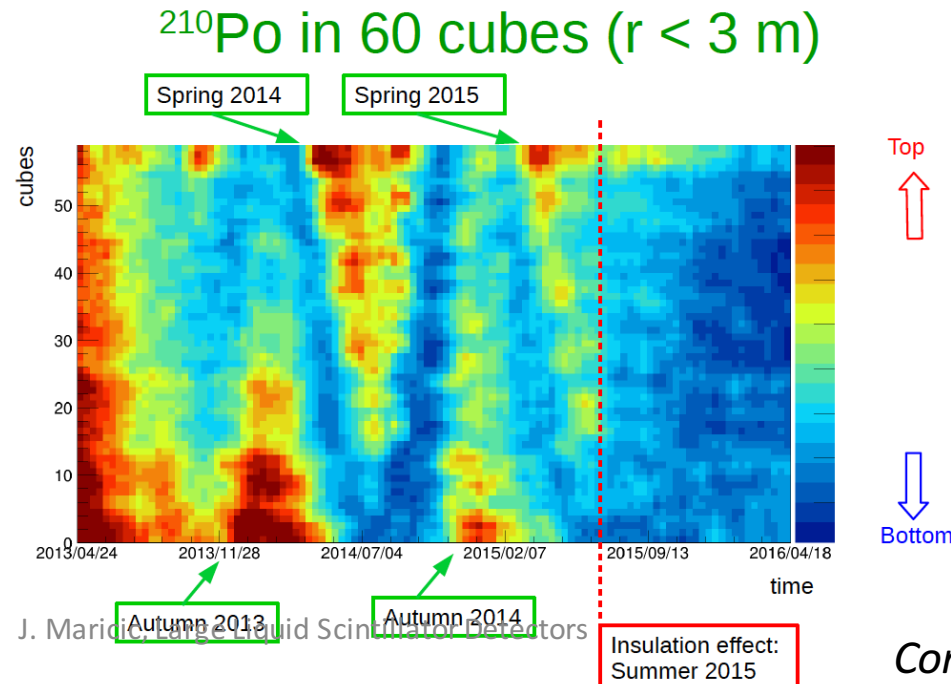
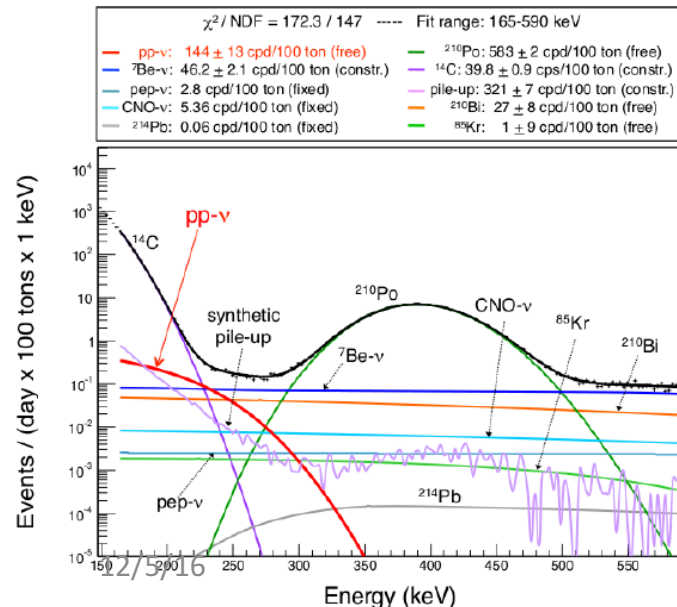
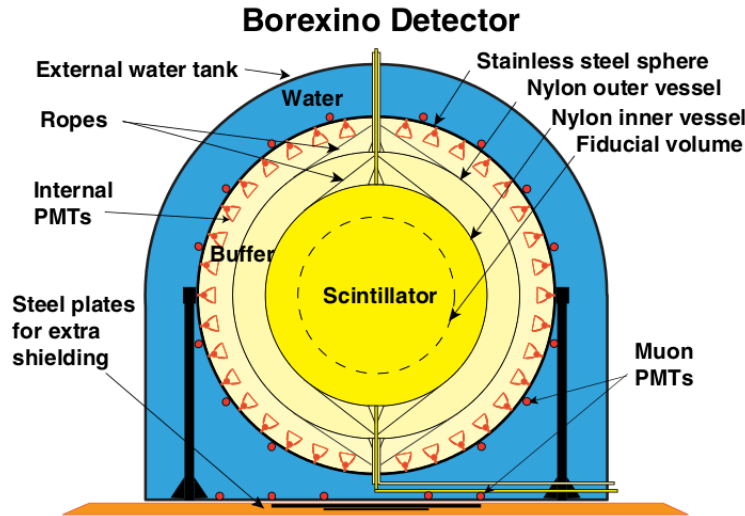
in connection with Hyper-Kamiokande

target sensitivity 8 meV

# Highlights and Interesting Points from Borexino

- ✓ Similar design, two balloons
- ✓ Outstanding radiopure LS
- ✓ Were stalled for 2 years due to LS leak
- ✓ Incredibly low backgrounds
- ✓ Evidence for pp neutrinos
- ✓ Toward observation of CNO

Convection steers  $^{210}\text{Po}$  → problem  
Thermal insulation of Bx

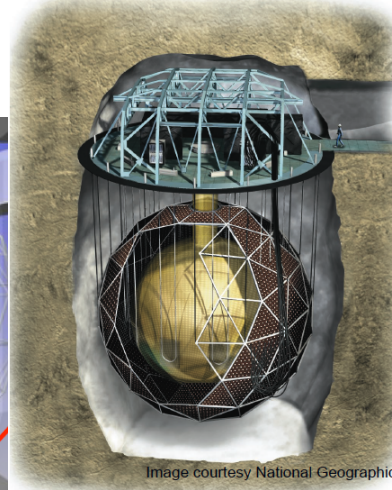
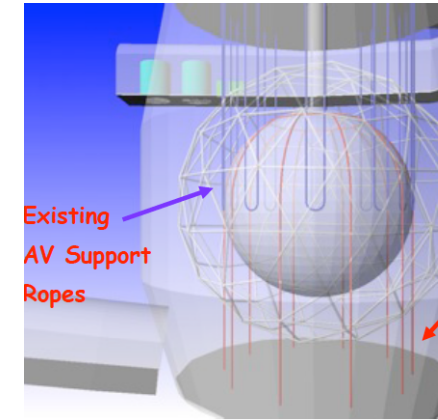


Convection seen in KamLAND too.



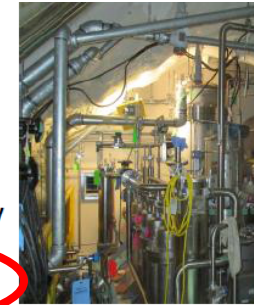
# SNO+ highlights and Interesting Points

- Converting Water Cherenkov into LS detector – huge effort
- Similar concept → acrylic sphere instead of balloon
- LLSD – 780 tons LAB loaded with Te for NDBD
- New LS and Te purification system, detector refurbishment, leak testing, ropes down...



## SNO+ Status

- Scintillator purification plant installed, commissioning under way
  - First LAB on site in a few months
  - Scintillator fill beginning spring 2017
- In the process of re-filling the detector with ultra-pure water
  - A few leaks in the cavity liner identified and repaired
  - New hold-down system for the acrylic vessel installed and fully tested
  - Making PMT repairs along the way
- Tellurium purification, installation underground beginning later this year
  - Loading system to follow in 2017
  - 1.8 T telluric acid (=1 T Te) stored underground for ~1 year now, 2.0 T telluric acid currently being shipped from supplier
- Tellurium loading early in 2018



Slide from 2016

Slide from 2010

## Status of SNO+ Construction

- SNO+ is fully funded and under construction
- major construction work in the cavity is beginning now
- scintillator purification system ordered, designed and being built; installation in Fall 2011
- some “dead” SNO PMTs are being removed, repaired, and replaced
  - it's not planned to repair all dead SNO PMTs; rather, while we have time, we have found many PMTs are easy to repair and easily accessed

12/5/16 □ schedule: scintillator filling to start in Spring 2012

# Summary

- Large liquid scintillator detectors are versatile
- Demonstrated simplicity and capacity of LS for loading with different elements
- Very low intrinsic backgrounds of LS, combined with minimal inactive detector material
- Proven purification and suppression of backgrounds in situ
- Self-shielding from external gammas and neutrons: high neutron capture cross-section → excellent neutron veto detectors for DM searches (see DarkSide talk)
- Relatively modest energy resolution affects their discovery potential for NDBD
- **Nevertheless, LLSD are an attractive option for low energy rare event searches (few hundred keV to MeV range) since...**
  - Low intrinsic background combined with large volume makes them suitable for high sensitivity searches and charting unexplored parameter space
  - Active, high efficiency neutron veto for DM and maybe more than that
- Future detectors show promise of much improved energy resolution

